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PERMAFROST

V. P. Dadykin

/Maps referred to herein are appended./

The first reports on the existence of permafrost in Siberia date as far back as the 17th century.

In 1827, a merchant named Shergin began to dig a well in the city of Yakutsk. After several years of hard labor he was still unable to reach water and, having dug about 116 meters Shergin abandoned his undertaking. This well, which came to be known as the Shergin Shaft, was used by Middendorf as the prime example for his work of studying the temperature of the permafrost. To Middendorf belongs the credit for definitely establishing the presence in Siberia of perpetually frozen strata occupying an enormous area.

At the end of the 19th and in the beginning of the 20th century, information on this geophysical phenomenon accumulated rather rapidly. This was the time of the planning and construction of the great Siberian railroad. The engineers were confronted with the problem of overcoming the unique difficulties of construction and operation of a railroad in a region of permafrost.

Upon completion of the railroad, a wave of immigrants from European USSR poured into Siberia, particularly into the Transbaykal and Yakut regions. Numerous soil, geobotanical, hydrotechnical, and surveying expeditions and parties were working at that time in the permafrost areas, preparing tracts for the settlers. In many places, the thickness of the permafrost stratum was measured, and the presence of permafrost was established under the beds of some rivers. Solutions to many practical problems of construction were found. Certain relationships were established between agriculture and soil permafrost. But this was not yet a systematic investigation of permafrost.

In the second quarter of the 20th century, the opening of the northeastern regions of the Soviet Union necessitated thorough study. In 1930, in the staff of the Academy of Sciences USSR, on the initiative of Members V. I. Vernadskiy and M. I. Sumgin, a commission was organized for the study of permafrost. The

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commission considerably enlarged our knowledge of the nature of permafrost in the first years of its work. In 1936, the commission was reorganized into the Committee on the Study of Permafrost (Komitet po izucheniyu vechnoy merzloty). Since that time, the expedition's investigation has been supplemented by regular observations at the Committee's permafrost stations in Vorkuta, Igarka, Yakutsk, and Anadyr'. In 1939, the Committee was reorganized into the Permafrost Research Institute (Institut merzlotovedeniya). The Institute adopted the name of Academy Member V. A. Obruchev, the permanent chairman of the commission, of the Committee, and then Director of the Institute.

Our information on permafrost is being crystallized into a new branch of science, an independent science called permafrost research. Special works on permafrost investigations are being published. A series of monographs have appeared. In the University of Moscow a course has begun on permafrost research. The first general textbook on permafrost appeared in 1940. Since 1946, a periodical, Merzlotovedeniye (Permafrost Studies), has been published.

Systematic scientific work on the investigation of this peculiar natural phenomenon has made possible the rapid accumulation of information about it, and it is now considerable.

The first problem confronting the geographer is that of the spatial distribution of permafrost. Attempts to delineate the regions of permafrost distribution applicable to the territory of USSR on a map are ancient. As the data on permafrost has accumulated, the boundaries of its distribution have become more definite. In 1945, in the Permafrost Research Institute, V. F. Tumel' drew up a new map of the distribution of permafrost within the territory of the USSR, drawing on all the factual material available at that time /see map 1/.

Map 1 differs materially from the previous one, published in 1937 by M. I. Sumgin /see map 2/. In preparing his work, Sumgin was able to rely on approximately 800 cross sections. Tumel', however, had 2,000 cross sections available. But for the enormous territory occupied by permafrost, even this is extremely little. In addition, the data is distributed quite unequally over the territory. Up to the present, there are still huge areas untouched by a permafrost explorer, for instance, between the Yenisey and Lena rivers. Generally speaking, the investigation of permafrost is still not broad, and the permafrost investigators face a great task. However, the available data permits noting some spatial regularity. The region of permafrost prevalence in general is the north and east; southward it decreases, and the extreme north of Europe, Scandinavia and the Kola Peninsula, is almost free of it. In the east, it sweeps far down to the south and in the Transbaykal area it enters Mongolia, beyond the confines of the USSR. Particular note should be made of the presence of small permafrost "islands" in mountainous regions, in the Urals, the Pamirs, and the Caucasus.

Besides the Eurasian continent, permafrost extends over almost the whole territory of Alaska and a considerable part of Canada; it also appears in Greenland and in most of the islands of the Arctic Ocean. However, this phenomenon has been little studied abroad, including North America. Documentation for this statement will be found in the summary of foreign data on permafrost, compiled in 1940 by L. A. Brattsev, and on the map of the southern limits of the area of permafrost in North America /omitted/.

In the Antarctic, perpetually frozen strata are still more widespread than in the northern hemisphere, but available information is so fragmentary that to date it is impossible to sketch on the map even an approximate boundary of its distribution.

As may be seen from the maps mentioned above, vast areas are in the grip of permafrost. V. F. Tumel' estimates that this phenomenon is spread over almost 25 percent of the entire land area of the earth. Within the territory of the Soviet Union, permafrost is found in approximately an area of 10 million square kilometers, equivalent to about 49 percent of the total territory of the USSR.

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This is more than the area of all of Europe. So wide a distribution of this phenomenon demands a thorough study, especially since permafrost, as is shown later, exerts a tremendous influence on various aspects of man's economic activity. The huge resources to be found in permafrost territories compel the surmounting of all difficulties arising in their exploitation. Of the natural resources found in the permafrost zone we may mention the already workable coal deposits in Vorkuta, metals in Noril'sk, salt in Nordvik, tin in Verkhoyansk, and gold in Kolyma, Aldan, and Aladh-Yun.

How did permafrost originate in the ground?

The appearance of a permafrost layer in a stratum of the earth's crust is due primarily to a deficit in the annual heat balance. The upper stratum of the earth's crust is subject to the influence of a thermal flow from the depths of the earth, which although not large, is still characterized by a great constancy. It is estimated that the quantity of heat coming from the depths of the earth amounts to 41 to 54 small calories per year per square centimeter of the earth's surface, about one five-hundredth of the heat received from the sun. The earth's surface, in addition, receives in the course of the year two more great thermal waves, admittedly not very constant from year to year: the wave of summer heating and the wave of winter cooling. If, in the course of a series of years, the negative thermal flow, winter cooling, exceeds the positive, there appears in the soil a layer that does not thaw during the warm season of the year. Even if, after some time, a change occurs in the climate and the flow of heat into the soil is equal to the outflow, the permafrost will still remain. Accordingly, the development of permafrost is due primarily to the climatic conditions of the region.

The development and persistence of permafrost are possible only in regions with a negative annual mean temperature of the air. They depend, to a considerable degree, on a series of elements in the natural composite, first of all, on the character and condition of the soil and ground, their mineralogical and granulometric composition, structure, humidity, color, and thermal properties.

A great influence on the thermal cycle in the soil is exerted by such factors as vegetation and snow cover. For instance, a thick cover of vegetation absorbs the flow of radiant energy by its parts above ground, preventing it from reaching the soil. In winter, the vegetation acts to reduce the loss of heat from the soil. The snow cover also serves as a heat-insulating layer, keeping the soil warm in the winter months. In the spring months, a thick snow cover, remaining on the surface of the ground, produces a great delay in its heating by solar radiation.

Note should be taken of the special role of soil humidity in the heat exchange of the soil, to be explained satisfactorily by the considerable magnitude of the latent heat of ice freezing and ice thawing (80 small calories per cubic centimeter of water). The freezing stratum of soil, releasing heat, retards the cooling of the lower strata. During thaw, the opposite picture is observed: the thawing layer, absorbing the heat, retards the warming of the lower soil layers. A barrier is created to the circulation of heat in the soil, in the form of a soil stratum of zero (0 degrees Centigrade) temperature. This barrier has received the designation of "zero curtain." The greater the humidity of the soil, the thicker the zero curtain.

Most likely, this great accumulation of cold in the strata of the lithosphere took place during the period immediately following the ice age in Eurasia and North America, and the presently observed distribution of permafrost appears to be a residue of the postglacial epoch. Present-day climatic conditions merely increase or diminish the store of cold in the soil and produce an "aggradation" or a "degradation" of the permafrost, depending on regional peculiarities. /By "degradation" of the permafrost is meant the process of diminishing the quantity of stored cold in a stratum of perpetually frozen ground. "Aggradation" is the process of increasing the quantity of stored cold./

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In recent years in the northern hemisphere an increase in the warmth of the climate has been noted. It has been determined that the quantity of ice in the Barents and other Arctic seas has diminished, and a steady retreat of glaciers on the islands has been observed; in the northern areas, species of fish have appeared which were never before found there because of the low water temperature. In the last 50 years the annual mean temperature of the air in Mezen' has risen 1 degree Centigrade, which, for an annual mean, is a quite significant magnitude.

The noted warming of the climate over a century is the main cause of the degradation of the permafrost, indubitably established for series of regions. Shrenk, visiting the city of Mezen' in 1837, pointed out the presence of permafrost there. Ninety-six years later, an expeditionary commission was working in the same area and detected no permafrost either in Mezen' or in its environs. Clear indications of degradation have been established in areas along the course of the Usa River, a tributary of the Pechora, and along the middle course of the Ob' and Yenisey rivers near Skovorodino station on the Transbaykal Railroad and elsewhere. In general, it may be stated that the regions where degradation of permafrost has been established are distributed along the southern boundary of the permafrost.

Not infrequently the cause of change in the amount of stored cold in the ground is human activity. Man cuts forests, breaks the soil, erects buildings and factories. All this disturbs the established thermal regime of the earth's upper strata and leads to changes in the stored quantity of cold in the soil.

A very widespread component in the cross section of permafrost strata is ice that has turned into a kind of rock. The designation "fossil ice" (or mineral ice) has been accepted in the literature for this stony ice. Subterranean ice sheets sometimes reach a very great thickness. In the southwestern part of the Taymyr Peninsula the thickness of the fossil ice reaches 15 meters, and along the Aldan River, at the Tynda settlement, ice thicknesses up to 25 meters have been observed. The thickness of the ice cliff in the region of the mouth of the Yana is over 69 meters. The greatest measured thickness of buried ice has been reported for Bol'shoy Lyakhovskiy Island, where it amounts to about 80 meters. The thickest masses of subterranean ice have been traced between the mouth of the Lena and Chaunskaya Bay, as well as in northwestern Alaska. In these regions the thickness of the ice sheets amounts to tens of meters, and their area several tens of square kilometers. Deposits of fossil ice are widespread in the central Yakut where the extent of these formations in the ground is several hundreds of kilometers.

Investigations have shown that the origin of these ice strata is extremely varied. In some cases, they are remnants of the glacial epoch. In other cases, the fossil ice is more recent, representing buried snowfields, or the buried ice of ice-covered fields, or a frozen lake buried in earth, or, finally, river ice thrown up on the banks and buried in earth.

The distribution of the permafrost in the soil is not continuous. Even in extreme northern regions one can find areas free of permafrost, e.g., under large rivers and lakes, the so-called thawed spots (taliks). Sometimes areas are found where the surface of the permafrost is not immediately underneath the seasonal frozen soil, but sometimes tens of meters down. Such areas have been designated pseudo-thawed spots. As one moves southward, the area occupied by thawed spots increases, and at the very southern limit of the permafrost the thawed ground is predominant, with the permafrost found in "islands."

Sumgin defined an area of permafrost prevalence in terms of the correlation of the areas of thawed spots and permafrost. However, the division of territory on the principle of correlation of thawed and frozen areas at the present time is insufficient for the characteristics of permafrost. Accordingly, the differentiation proposed by Tumel' of regions of distribution of permafrost according to the thickness of the perpetually frozen stratum, and the map compiled by him, are the first efforts made to outline regions on the basis of this principle.

From figures furnished on the basic map by Tumel' it appears that the area having permafrost of thickness: up to 15 meters represents about 14 percent; 15-35 meters, about 10 percent; 35-60 meters, about 8 percent; 60-120 meters, about 12 percent; 120-250 meters, about 21 percent; 250-500 meters, about 30 percent; and over 500 meters, about 5 percent.

What is the temperature of the permafrost layer?

Measuring the temperature of a permafrost layer involves great technical difficulties. It is impossible without deep drilling which requires special equipment. Considering that many regions of permafrost are still thinly populated and little frequented, the paucity of data on the thermal regime of frozen soils is understandable. Although the painstakingly performed temperature observations of Middendorf in the Shergin Shaft are questioned, they are still being quoted to this day. We offer figures obtained by this investigator in 1844-1848:

Depth (in m)	Mean Annual Temperature (in °C)
2.13	-11.18
4.57	-10.19
6.10	-10.16
15.24	- 8.26
30.48	- 6.52
45.72	- 5.80
60.96	- 4.85
76.20	- 4.18
91.44	- 3.89
106.68	- 3.41
116.43	- 3.00

From examination of this table it is evident that the temperature of the permafrost layers increases with depth. Middendorf made use of this fact for determining the magnitude of the geothermic gradient. He estimated that the annual temperature fluctuations in the Shergin Shaft extend to a depth of 100 feet (30.48 meters). He, therefore, calculated the geothermic gradient with that depth as his starting point, and determined it in round numbers at 1 degree Reaumur (1.25 degrees Centigrade) per hundred feet. Using this value, Middendorf calculated the thickness of the permafrost in Yakutsk at approximately 200 meters.

It should be noted that the thickness of permafrost, as found in recent years by deep drilling in Yakutsk, almost coincides with Middendorf's estimate. In the drillings, permafrost was noted to 216 meters. There are several stations occupied with the measurement of the soil temperature: near the southern boundary of the permafrost at Skovorodino station on the Transbaykal Railroad, to a depth of 28 meters, in the city of Petrovsk-Zabaykal'sk (to 18 meters), in the basin of the Usa and Vorkuta rivers, and in other places. At Anadyr', temperature measurements of the permafrost were made by P. F. Shvetsov, to a depth of 31 meters:

Depth (in m)	Temperature (in °C)
5	-5.7
10	-5.4
15	-5.5
20	-5.6
25	-5.6
30	-5.5
31	-5.5

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In the Verkhoyansk range, measurements to a depth of 22 meters showed temperatures of -7.7 to -7.9 degrees Centigrade.

The permafrost layers are located at a certain depth below the surface. During the warm season of the year the upper layers of the earth thaw and acquire positive temperatures, and the top limit of the permafrost subsides to a certain depth. This summer-thawed layer of the soil has been designated the "active layer." Its thickness fluctuates between rather great limits, from 30 to 40 centimeters to several meters. The intensity and depth of thawing depend primarily on the nature of the ground itself and its moisture. In addition, a tremendous role is played by the thickness of the snow cover and the nature of the vegetation. Fallen autumn leaves, dead pine needles, and scattered manure, all this dictates the depth of the permafrost. The active layer, no matter how thick, is the medium for the development of all of the biological phenomena in the regions of permafrost. In the thawing layer of soil, plants and even mighty trees develop. In this layer the microbiological processes of decomposition of masses of organic substances and their reduction to the elements of soil food for plants also occur.

Because of this, the landscape in regions of permafrost, when viewed superficially, does not differ from the landscape of regions free of permafrost. Only attentive and thoughtful observation of the scene allows one to note the unsuspected presence and effect of a powerful source of cold. Trees overturned by storms in the forest show an absence of roots reaching deep into the ground, and instead a great number of root sprouts creeping in the upper layers of the soil.

Then, there is the interest in the peculiarities of the hydrologic pattern in regions of permafrost distribution. Subterranean waters in the permafrost regions are commonly divided into three categories:

The first category is above the water-impermeable stratum of the permafrost where lie the "suprapermafrost waters" (nadmerzlotnaya voda), which are subject to seasonal changes from the liquid phase to the solid, and back. The underlying permafrost, even in the summer months, is a water-impermeable base for these suprapermafrost waters.

The second category, the "intrapermafrost waters" (mezhmerzlotnaya voda), is found within the permafrost stratum in both the liquid and the solid phase. The solid phase, fossil ice, is the most frequent form of intrapermafrost waters. However, within permafrost strata the liquid phase of these waters is also found. The liquid intrapermafrost waters, unlike the suprapermafrost waters, are in a relatively stable condition and are not subject to the seasonal freezing and thawing. Between the water in the liquid state and the permafrost layer there exists a deep incompatibility. The water, yielding its thermal energy to the frozen ground, strives to bring it out of its frozen state. The perpetually frozen ground, in turn, absorbing the thermal energy of the water, strives to transform the water into ice. The result is a sort of dynamic equilibrium between the unfrozen water and the frozen ground.

The third category, the "subpermafrost waters" (podmerzlotnaya voda), lies underneath the stratum of permafrost. These waters are always in the liquid phase. The water is usually found under pressure, and when water-bearing layers are perforated by drilling, the water not infrequently gushes from the bore hole. In Yakutsk, drillings opened great water-bearing sheets at a depth of 250-300 meters. At present, investigation of the water yielding capacity of the borings with a view to utilizing the subpermafrost waters for municipal water supply is being concluded.

Rivers flowing in areas of permafrost prevalence have a very high discharge coefficient in the spring, and a very unequal discharge by seasons. According to observations, on the Yana River near the city of Verkhoyansk, the discharge amounts to 5.2 percent of the annual discharge for the winter, 13.2 percent for

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the spring, 68.0 percent for the summer, and 13.6 percent for the fall. Corresponding data for the Indigirka near Krest-Mayor are: winter 6.5 percent, spring 14.5 percent, summer 63.8 percent, and fall 15.2 percent. The reason for this is again the permafrost which, being impermeable to water, causes the rapid runoff of summer precipitation and water from melting snow in the warm portion of the year; hence, in summer, and not in spring, are floods observed in northern regions.

During the cold part of the year, the rivers are fed to a considerable degree by subpermafrost springs, the number of which is relatively small, and their discharge is also much subject to fluctuations.

In regions of permafrost, it is frequently possible to observe that a river-bed freezes, the surplus water runs off, and a hollow, airspace forms under the ice. Sometimes several sheets of ice may be noted. This is the so-called "dried ice" (led-sushnyak). Wrangel himself told how one of the horses of his caravan fell with its full load through the ice of the Dogdo River. "The Yakut guides, seeing my accident, laughingly ran to my assistance, assuring me that they would get the horse out not merely alive, but not even wet. When they broke the ice I saw that the river water had almost all run out." The horse, entirely unharmed, was standing on the bottom.

In many cases, the solid freezing of a river gives rise to the formation of layers of ice. If the winter cold has solidified the river and has frozen it to the bottom, and there is an active spring somewhat above that place, the emergent water, having no outlet and accumulating against the ice chamber, develops pressure. The compressed water seeks an outlet and breaks through at the weakest spot, flooding the ice surface and the river lowlands. In a short time, the cold turns this water into ice. As new volumes accumulate, the water again breaks through and overflows. Often, in this way, great ice masses are frozen during a winter. Intense cold makes possible the freezing of the river-bed and, consequently, the formation of ice layers. This icing water is a serious risk to travelers.

Of course, in regions of permafrost, it is not only on rivers that ice phenomena are observed. At the point of outlet of any perennial spring the appearance of an ice layer is possible as a consequence of the freezing up of the runoff channels for the emergent water and its continued emergence from below.

Sometimes the bursting of the compressed water through the ice armor is accompanied by loud explosions reminiscent of an artillery cannonade.

Ice layers make roads impassable. For protecting roads and other installations from icing, so-called freeze strips, consisting of wide shallow ditches laid out across the course of the subterranean flow, but not exposing it, are successfully used. These ditches insure the solid freezing of the ground at that place, as a consequence of which the flow is intercepted above the installation that must be protected from icing, and the icing itself is, so to speak, diverted elsewhere.

The influence of permafrost on the economic activity of man is extremely varied and significant. Permafrost makes its presence known with every change in the natural conditions of the locality. A simple path laid in snow, by compacting the snow, intensifies the freezing of the soil at that place and can become the cause of the formation of an icing layer. A post driven into the ground will in 2 to 3 years be pushed out of the ground by the heaving effort, if no special measures are taken. A ploughed field in 3 to 4 years may turn into a swamp or even a lake, since ploughing greatly increases the absorption of heat by the soil, leading to the thawing of the buried ice. Sometimes a house built on permafrost after a few years suffers serious deformation and even complete destruction, if no preventive measures are taken.

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Earthwork under permafrost conditions is quite unique. Working the ground in the wintertime under frozen conditions is extremely difficult in view of its hardness; it resembles work in rock. Working the same ground in the summertime leads to thawing of frost and, since in an area of permafrost the upper layers of the soil are usually in a supersaturated condition and from the soil-mechanics aspect they are predominantly fine-granular (dusty and clayey) deposits. At a time of thaw, a quicksand forms, in which the wheelbarrow of the digger sinks, and which reduces the digger himself to a state of immobility in the liquid pasty mass.

Mining and drilling operations in permafrost areas are characterized by a series of peculiarities. In drilling, there is the constant hazard of the freezing of flushing water, formation of ice plugs, and freezing of instruments. Sometimes ice excrescences interfere with the placing and removal of pipe. Experience in drilling work has suggested the use of heated instruments and of salt water for flushing. As is known, salt water freezes at a lower temperature than fresh water. In driving deep shafts and galleries, the perpetually frozen formations, often filled with interlayers of ice, threaten to shift and settle, a matter extremely difficult to anticipate. Difficulties also arise in concrete work, as concrete sets poorly at low temperatures and does not guarantee the necessary solidity. On the other hand, in some cases the permafrost permits dispensing with the shoring of drifts and pits, considerably reducing construction costs. Such works may be executed exclusively in winter. In summer, they are preserved and the working sites are carefully covered so that summer heat does not penetrate the frozen strata.

Builders particularly must keep permafrost in mind. Every structure erected in a region of permafrost prevalence alters the thermal regime of the base and leads to the accumulation or the thawing of permafrost under the structure. Changes in the thermal regime of the ground beneath a structure cause deformations of the foundation and resultant possible destruction of the installation. Builders anticipate the harmful effect of a permafrost base by storing the winter cold under a building for the summer period. This is accomplished by building a ventilated cellar.

Not a little influence is also exerted by permafrost on soil-forming processes and on conditions of plant growth. Permafrost occasions a lower temperature cycle in the upper layers of the soil, creating special conditions for all biological processes within it. Sumgin has shown that not all the thawed layer of soil can supply plants with water and nutritive substances, as the portion of the thawed layer lying directly next to the surface of permafrost has so low a temperature that in that portion of the thawed layer only the physical processes are possible. The physiological processes, absorption of water and nutritive substances by roots, activity of microflora, and the like, are inhibited. The majority of plants in a region of permafrost prevalence have adapted themselves to those conditions and have developed a root system spreading in the upper, better-warmed layers of the soil.

The whole integrated complex of problems of the influence of permafrost on biological phenomena is still little investigated. Besides, this is not the only field still requiring a large amount of wider and deeper exploration. Permafrost research is a very young science and still has many unsolved problems, both theoretical and applied, awaiting scientific elaboration.

[Appended maps follow.]

Map 1. Distribution of Permafrost in the USSR

(Compiled by V. F. Tumel' in 1945, Merzlotovendeniye (Permafrost Studies), Vol I, No 1, 1946)

1. Regions free of permafrost within permafrost areas

2. Regions of isolated islands of permafrost strata not thicker than 15 m

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3. Regions of wide distribution of permafrost strata not thicker than 35 m
4. Regions of permafrost strata of maximum thickness up to 60 m
5. Same, of thickness up to 120 m
6. Same, of thickness up to 250 m
7. Same, of thickness up to 500 m
8. Same, of thickness over 500 m
9. Northern boundary of regions with temperatures not lower than -10 degrees Centigrade at a depth of 10 m
10. Same, with temperatures not lower than -5 degrees Centigrade
11. Same, with temperatures not lower than -3 degrees Centigrade
12. Same, with temperatures not lower than -1 degrees Centigrade [sic]

Map 2. Distribution of Permafrost

(according to M. I. Sumgin)

1. Regions of permafrost with continuous ground temperatures mostly lower than -5 degrees Centigrade at a depth of 10-15 m
2. Regions with thaws having ground temperatures mostly from -5 degrees to -1.5 degrees Centigrade at a depth of 10-15 m
3. Regions where thawed spots (taliks) predominate, in the south, there are only isolated islands of permafrost
4. Boundary of the regions and islands of permafrost in the USSR
5. Permafrost only in the hummocks of peat marshes.

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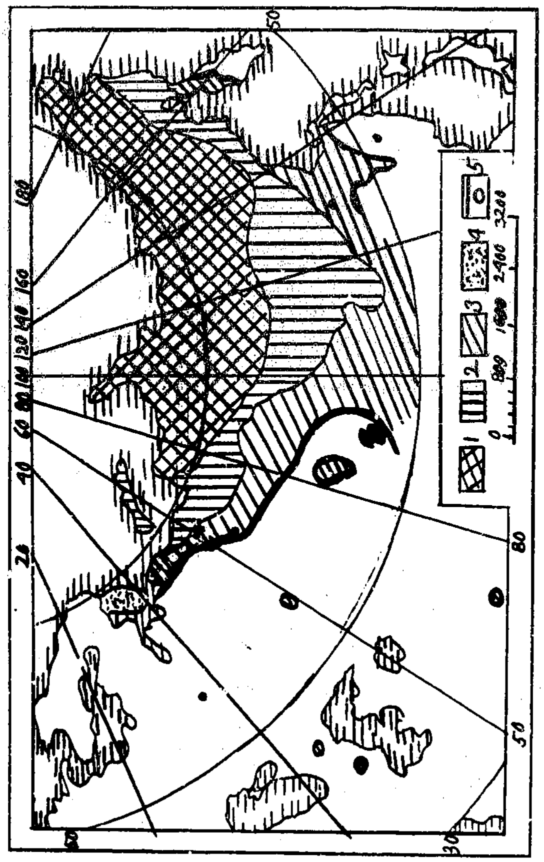

Map 1. Distribution of Permafrost in the USSR

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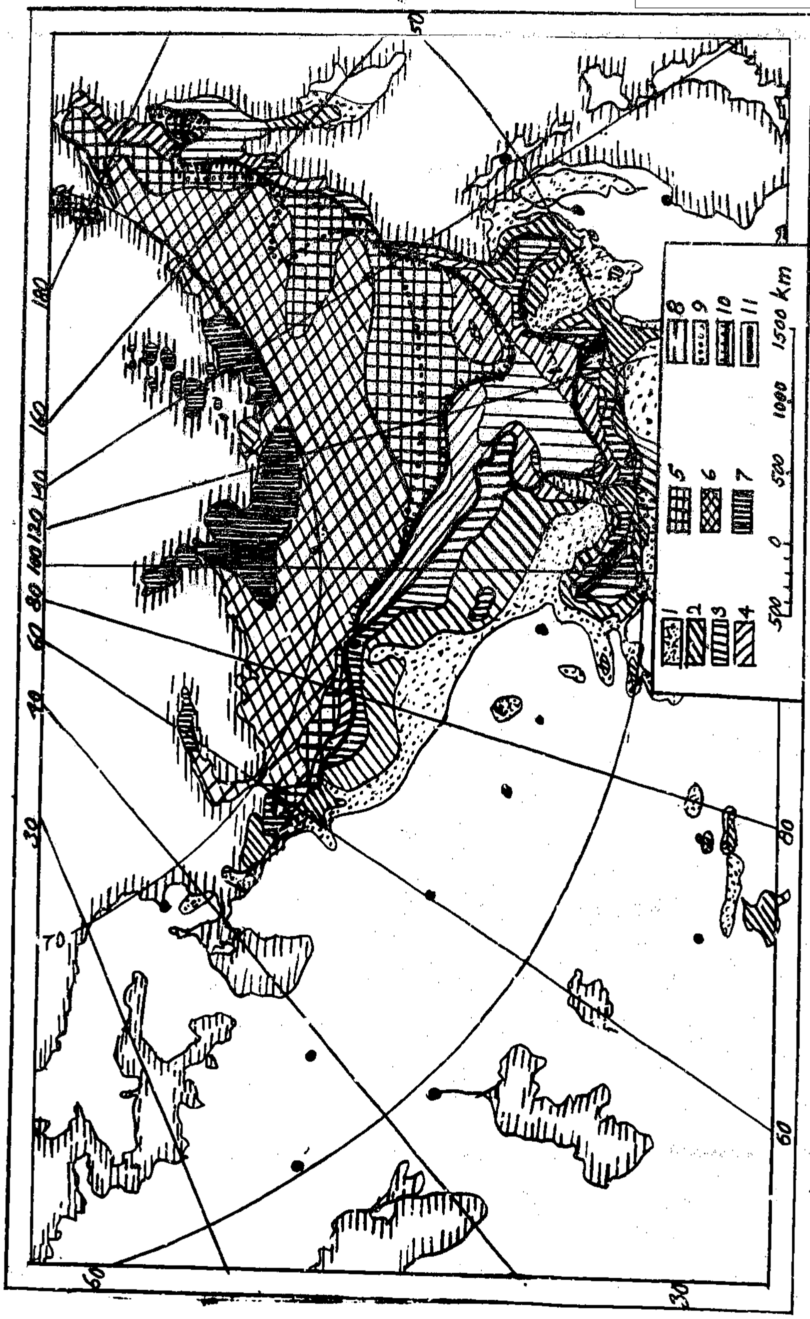

Map 2. Distribution of Permafrost

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